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CORRELATION BETWEEN THE EXCESS LOSSES AND THE RELATIVE PERMEABILITY IN FULLY FINISHED NON-ORIENTED ELECTRICAL STEELS

KORELACIJA MED ANOMALNIMI IZGUBAMI IN RELATIVNO PERMEABILNOSTJO V GOTOVIH NEORIENTIRANIH ELEKTROPLOČEVINAH

Gašper Novak[1], Janko Kokošar[1], Aleš Nagode[2], Darja Steiner Petrovič[3]

[1]RCJ, d. o. o., Cesta Franceta Prešerna 61, 4270 Jesenice, Slovenia
[2]Faculty of Natural Sciences and Engineering, University of Ljubljana, Aškerčeva 12, 1000 Ljubljana, Slovenia
[3]Institute of Metals and Technology, Lepi pot 11, 1000 Ljubljana, Slovenia
gasper.novak@acroni.si

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Using the modified Steinmetz equation and Bertotti's model, the correlation between the excess losses and the relative permeability of non-oriented electrical steel was investigated. Three different steel grades were used in the study: M530-50A, M400-50A and M350-50A. It was observed that both the excess losses and the relative permeability increase in the region of the low magnetic flux density; they both reach their peak values at 0.9–1.0 T, and then drop to the minimum values as the electrical steel is magnetized to saturation.

Keywords: electrical steel, Steinmetz equation, Bertotti's model, excess loss, relative permeability

Z uporabo modificirane Steinmetzove enačbe in Bertottijevega modela smo ugotovili korelacijo med anomalnimi izgubami in relativno permeabilnostjo v neorientiranih elektropločevinah. V raziskavi smo uporabili tri različne kvalitete: M530-50A, M400-50A in M350-50A. Ugotovili smo, da tako vrednosti anomalnih izgub kot tudi relativne permeabilnosti začnejo naraščati v območju majhnih gostot magnetnega pretoka, dosežejo svojo maksimalno vrednost v istem območju (med 0,9 T in 1,0 T) in se nato zmanjšujejo do minimalnih vrednosti, ko je jeklo tudi namagneteno do nasičenja.

Ključne besede: elektropločevine, Steinmetzova enačba, Bertottijev model, anomalne izgube, relativna permeabilnost

1 INTRODUCTION

A number of theories exist that describe the excess losses as the third component of the total core losses of fully finished, non-oriented electrical steel. Many authors have studied the mechanisms of their formation and there are many contradictory theories that can be found in the literature.[1–6] Generally, it is believed that the occurrence of excess losses is associated with the magnetic-domain structure, the geometry of the steel sheet, the stochastic interactions between so-called magnetic objects, the intrinsic dynamics of the switching between metastable states in elementary hysteresis operators, etc.[1–6]

A conventional loss-separation scheme per cycle describes the excess losses as exponentially dependent on the frequency[7] and was initially correlated with domain-wall movement as early as the 1950s.[8–10]

The principal equation used to estimate and separate the core losses was first introduced by Steinmetz[11], who developed an empirical equation for the hysteresis losses. The dynamic-loss component was derived from Maxwell's equations, and it is referred to as the classic eddy-current loss component.[12] Such models provide useful insights into the loss mechanism, but they do not accurately account for the excess losses. This third component was added as a result of the deviation between the measured and the calculated values and shows that the origin of the excess loss can be understood by describing the magnetization dynamics in terms of the domains and the domain-wall motion.[12,13]

In the 1980s, Bertotti developed a statistical theory to calculate the iron losses by introducing so-called magnetic objects, identified as individual domain walls in grain-oriented steels and as clusters of neighbouring domain walls in non-oriented steels, which led to a physical description and the function of the loss-factor C_{exc} in terms of the active magnetic objects and the domain-wall motion.[14–16] Whereas Bertotti ascribes the excess losses to domain-wall processes, there are several authors[3–6] who correlate the excess losses with the hysteresis losses and describe them as frequency-dependent hysteresis losses. Some authors have also reported negative excess-loss values obtained from calculations as a result of a neglected skin effect.[17,18]

In the present study, the core losses of different grades of fully finished, non-oriented electrical steels are separated using the modified Steinmetz equation and the added third component of the excess losses derived by Bertotti.[11,14] The correlation between the excess losses and the relative permeability of non-oriented electrical steels is investigated.

2 EXPERIMENTAL

2.1 Materials and sampling

Three different grades of fully finished, non-oriented electrical steels were chosen for the investigation. The designation of the grades is in accordance with the European Standard EN 10106[19], and is as follows: M350-50A, M400-50A and M530-50A. The samples contained the mass fractions w from 1.04 % to 1.88 % Si (**Table 1**). The thickness of the analysed samples was 0.50 mm ± 2 %. The grain size estimation was performed in accordance with the standard ASTM E112 – 10 (**Table 1**).[20]

2.2 Methodology

The electromagnetic properties were measured at room temperature using a standard method for measuring the core losses, i.e., an Epstein test using a Brockhaus Messtechnik Epstein frame. The range of measurements was defined with
$\{B_1, B_2..B_j..B_m\} = \{0.1\text{ T}, 0.2\text{ T}..1.5\text{ T}\}$, $m = 15$ and
$\{f_1, f_2..f_i..f_n\} = \{5\text{ Hz}, 10\text{ Hz}..100\text{ Hz}\}$, $n = 20$.
Before every measurement, the demagnetization process at 30 Hz and 2500 A/m was carried out to maximize the measuring accuracy, which is within 0.2 %, according to the manufacturer's guarantee.[21]

The core-loss measured data were used to plot the curves and to be analysed using a polynomial regression analysis. The measured total core losses P_t were then separated into the hysteresis, the classic eddy current and the excess component using a modified Steinmetz equation (Equation 1).[11] The excess-loss component per cycle (Equation 2) follows a simple $f^{0.5}$ law, and was proposed by Bertotti[1]:

$$P_t = P_{hys} + P_{eddy} + P_{exc} = \\ = k_{hys} fB^n + k_{eddy} f^2 B^2 + k_{exc.} f^{1.5} B^{1.5} \qquad (1)$$

$$\frac{P_t}{f} = k_{hys} B^n + k_{eddy} fB^2 + k_{exc.} f^{0.5} B^{1.5} \qquad (2)$$

Here P_{hys}, P_{eddy} and P_{exc} are the hysteresis, eddy-current and excess losses, respectively, f is the frequency and n is the Steinmetz coefficient. B is the flux density, k_{hys}, k_{eddy} and $k_{exc.}$ are the hysteresis, eddy-current and excess coefficients, respectively, which depend on the lamination material, the thickness, and the conductivity, in addition to other factors.[17]

Based on the determined coefficients, the hysteresis, eddy-current and excess losses were calculated and the behaviour of the excess losses for a given magnetic flux density was observed.

3 RESULTS AND DISCUSSION

The core-loss separation was made for three different grades of fully finished, non-oriented electrical steel con-

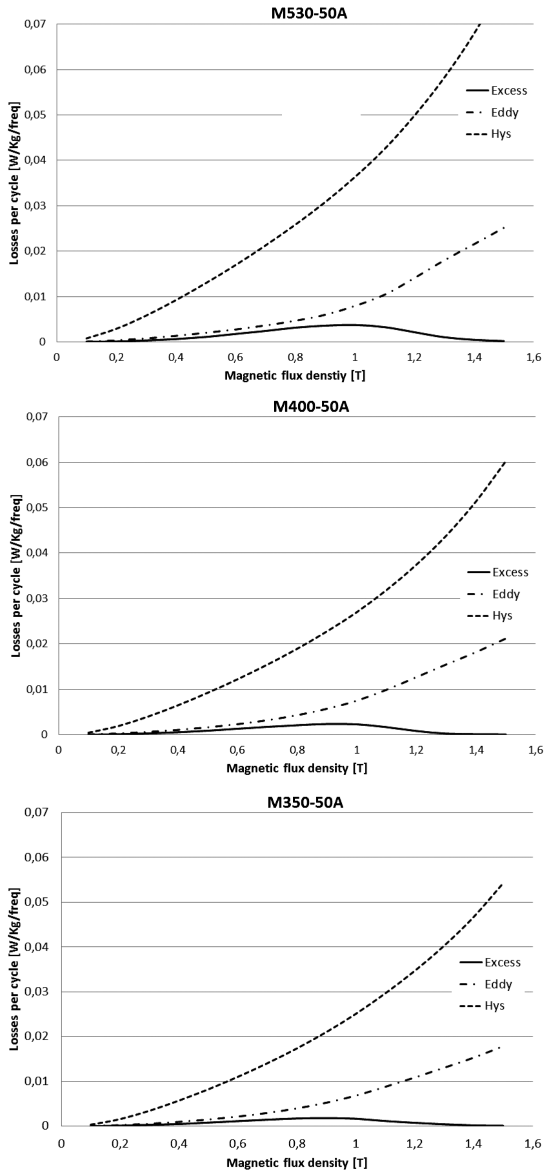

Figure 1: The aspect of the separated core losses per cycle for the investigated grades

Slika 1: Razdelitev močnostnih izgub na cikel v preiskovanih neorientiranih elektropločevinah

Table 1: Chemical composition (w/%) and estimated grain size of the investigated Epstein samples

Tabela 1: Kemijska sestava (w/%) in ocenjena velikost zrn preiskovanih Epsteinovih vzorcev

Grade	Si	Mn	P	Al	C	(Cr+Ni+Sn+Sb)	Cu	N	Mean grain size
M530-50A	1.04	0.22	0.025	0.115	0.0014	0.507	0.56	0.0054	8
M400-50A	1.50	0.28	0.018	0.234	0.0018	0.577	0.44	0.0057	6
M350-50A	1.88	0.23	0.028	0.539	0.0019	0.506	0.55	0.0037	5

taining from w = 1.04 % to 1.88 %. Si. Their mean grain sizes were estimated in accordance with the standard ASTM E112 – 10[20] and were as follows: 8 for grade M530-50A, 6 for grade M400-50A, and 5 for grade M350-50A. Although it is known that the anomalous losses are proportional to the square root of the grain size[22], this correlation may only be taken into account when comparing samples of very similar chemical compositions.

Normally, a conventional loss-separation scheme per cycle describes the excess losses as exponentially dependent on the frequency.[4]

In the present study, the separated core losses per cycle were calculated on the basis of the modified Steinmetz equation and Bertotti's model[15,16,23], the polynomial regression analysis and the method of least squares. Then, the coefficients for the hysteresis, the eddy-current and the excess losses were determined (**Figure 1**).

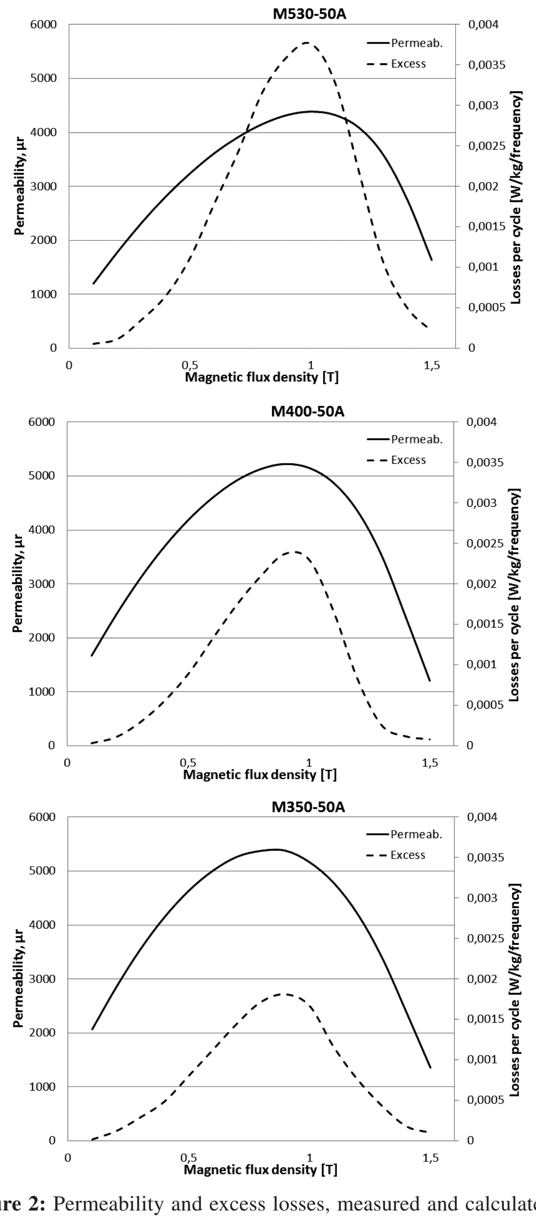

Figure 2: Permeability and excess losses, measured and calculated at 50 Hz in a sinusoidal waveform

Slika 2: Izmerjene vrednosti permeabilnosti in izračunane vrednosti anomalnih izgub za sinusoidni signal pri 50 Hz

While the eddy-current and hysteresis losses per cycle increase exponentially with an increasing magnetic flux density B, the excess losses show a different type of behaviour. It is clear that at the beginning of the magnetizing process the excess-losses component also increases with the magnetic flux density B until it reaches its peak value at a certain value of the magnetic density and then decreases towards higher values of B (**Figure 1**). These results contradict the data reported in the literature.[16,22,24]

In a next step, we considered in more detail the behaviour of the excess losses and compared it to various measured magnetic quantities. Surprisingly, a strong correlation with the peak values of the relative permeability curve was observed (**Figure 2**).

The excess losses and the relative permeability both reach their peak values in the same magnetic flux density region (at 0.9–1.0 T) and drop to the minimum values as the electrical steel is magnetized to saturation.

As is clear from **Figure 2**, both the permeability and the excess-loss curves for the grade M530-50A reach a maximum at 1.0 T, and for the grades M400-50A and M350-50A this maximum occurs at 0.9 T. The maximum achieved permeability for M530-50A is 4402.25 at 1.0 T, while the values are 5223.90 for the grade M400-50A and 5378.82 for the grade M350-50A, both at 0.9 T. The excess-loss curves follow the same shape. The excess-loss curve for the grade M530-50A reaches its peak value at 1.0 T, i.e., 3.762 × 10^{-3} W/kg, while the grades M400-50A and M350-50A have their maximum excess losses at 0.9 T, i.e., 2.371 × 10^{-3} and 1.809 × 10^{-3} W/kg (**Appendix 1**).

With an increase in the silicon content the total core losses decrease (**Table 1**), but this results in a lowering of the high induction permeability (**Figure 2**). However, the excess losses decrease with an increase in the magnetic flux density, in a similar way to the relative permeability. The magnetization curve has a characteristic shape for the ferromagnetic materials. It has its own limit for the flux density that can be obtained in a material that reaches its saturation point. It is assumed that in the low induction region domain movement prevails, and therefore the value of the relative permeability increases. In contrast to this, in the high induction region, i.e., above 0.9 T and 1.0 T, domain rotation prevails and the material approaches the saturation point. Consequently, the value of dB/dH is lowered, and thus the relative permeability is decreasing.

The energy dissipation mechanisms in electrical steels are associated with the displacement, nucleation and annihilation of domain walls, where the main mechanism of energy dissipation is domain-wall movement. The results of our investigation reveal that most of the anomalous loss activity takes place in the low induction region, which corresponds to the literature findings of Almeida et al.[25] The excess loss decreases in the high induction region, where the magnetization by irreversible magnetic-domains rotation prevails.[26,27] Therefore, it may also be assumed that the influence of active moving magnetic objects is significantly reduced for higher applied magnetic flux densities, e.g., above 1.0 T.

4 CONCLUSIONS

In this study, the correlation in the behaviour of the excess losses and the relative permeability during magnetization was shown for three different, fully processed, non-oriented electrical steel sheets of the grades M530-50A, M400-50A and M350-50A.

The excess losses and the relative permeability both reach their peak values in the same magnetic flux density region (0.9–1.0 T) and drop to the minimum values as the electrical steel is magnetized to saturation.

The results indicate that the applied magnetic flux density has a similar effect on the excess losses and the relative permeability for the three tested grades of non-oriented electrical steel.

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Appendix 1: Calculated excess losses and measured values of permeability at 50 Hz. The peak values are in bolded text.
Priloga 1: Izračunane anomalne izgube in izmerjene vrednosti relativne permeabilnosti pri 50 Hz. Največje vrednosti so označene s krepkim tiskom.

	M530-50A		M400-50A		M350-50A	
B/T	Excess loss	Permeability	Excess loss	Permeability	Excess loss	Permeability
0.1	5.48526E-05	1207.335473	3.26462E-05	1670.993781	1.70316E-05	2069.202745
0.2	0.000115822	1776.858355	0.000105316	2417.877413	0.000121357	2852.410355
0.3	0.000355771	2319.007755	0.000288051	3094.036454	0.000291277	3554.90471
0.4	0.000649753	2806.607734	0.000549347	3684.662644	0.000487962	4150.858388
0.5	0.001117573	3238.267234	0.000887329	4185.415238	0.000804304	4637.829184
0.6	0.001784936	3608.438528	0.001318661	4596.369363	0.001127032	5008.941024
0.7	0.002434541	3915.22099	0.001739806	4916.964717	0.001451237	5267.213506
0.8	0.003168208	4157.228566	0.002095731	5129.811213	0.001719809	5375.717946
0.9	0.003597262	4325.188334	**0.002371753**	**5223.901779**	**0.001809972**	**5378.82006**
1	**0.003762668**	**4402.255492**	0.002300389	5151.979896	0.001666607	5163.517918
1.1	0.003281045	4349.223616	0.001674421	4880.459866	0.001157574	4780.027201
1.2	0.002170156	4105.246371	0.000830532	4356.258894	0.000750376	4193.891075
1.3	0.001060658	3600.67542	0.000256091	3533.655569	0.000431254	3394.49198
1.4	0.000494975	2764.035374	0.000117331	2390.975573	0.000184564	2390.724617
1.5	0.000212132	1647.469046	0.000084565	1206.236952	0.000145677	1357.413794